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Advances in Space Research 50 (2012) 427–440

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Plasmaspheric electron content derived from GPS TEC and FORMOSAT-3/COSMIC measurements: Solar minimum condition

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Received 5 December 2011; received in revised form 31 March 2012; accepted 2 April 2012
Available online 10 April 2012

Abstract

The plasmaspheric electron content (PEC) was estimated by comparison of GPS TEC observations and FORMOSAT-3/COSMIC radio occultation measurements at the extended solar minimum of cycle 23/24. Results are retrieved for different seasons (equinoxes and solstices) of the year 2009. COSMIC-derived electron density profiles were integrated up to the height of 700 km in order to retrieve estimates of ionospheric electron content (IEC). Global maps of monthly median values of COSMIC IEC were constructed by use of spherical harmonics expansion. The comparison between two independent measurements was performed by analysis of the global distribution of electron content estimates, as well as by selection specific points corresponded to mid-latitudes of Northern America, Europe, Asia and the Southern Hemisphere. The analysis found that both kinds of observations show rather similar diurnal behavior during all seasons, certainly with GPS TEC estimates larger than corresponded COSMIC IEC values. It was shown that during daytime both GPS TEC and COSMIC IEC values were generally lower at winter than in summer solstice practically over all specific points. The estimates of PEC ($h > 700$ km) were obtained as a difference between GPS TEC and COSMIC IEC values. Results of comparative study revealed that for mid-latitudinal points PEC estimates varied weakly with the time of a day and reached the value of several TECU for the condition of solar minimum. Percentage contribution of PEC to GPS TEC indicated the clear dependence from the time with maximal values (more than 50–60%) during night-time and lesser values (25–45%) during day-time.

Keywords: Plasmasphere; Ionosphere; GPS; Total electron content; FORMOSAT-3/COSMIC; Solar minimum

1. Introduction

Nowadays the measurements of Global Positioning System (GPS) are widely used by the scientific community for the Earth's ionospheric studies. The dense network of GPS receivers (a few thousands all over the world) fulfils simultaneous coverage in global scale with high temporal resolution. The height of GPS/GLONASS orbits is about 20,200 km above the Earth's surface, and so most part of the propagation path of a radio signal from a GPS satellite to ground-based GPS receiver or GPS receiver onboard a Low Earth Orbit (LEO) satellite is mainly within the plasmasphere. As the electron densities in the plasmasphere are several orders of magnitude less than in the ionosphere (e.g. Gallagher et al., 2000), the plasmasphere is often ignored at analysis and estimation of GPS TEC data, however the plasmaspheric contribution to the GPS TEC can become significant under certain conditions.

The total number of electrons along a ray path from GPS satellite to ground-based receiver is called total electron content (GPS TEC), this value is composed mainly by ionospheric electron content, IEC, and plasmaspheric electron content, PEC. So the contribution of PEC to the GPS TEC can be estimated from the simultaneous measurements of GPS TEC and IEC. Estimates of IEC

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http://dx.doi.org/10.1016/j.asr.2012.04.002

can be retrieved as a result of integration of ionospheric electron density profiles (EDP). For this aim one can use EDPs derived from model calculations, e.g. International Reference Ionosphere (Bilitza, 2001), or ground-based ionosonde measurements (Huang and Reinisch, 2001). At the first case we deal with model simulation results and there are a number of papers with PEC estimation by comparison with SUPIM (Sheffield University Plasmasphere Ionosphere Model) results (e.g. Lunt et al., 1999; Balan et al., 2002). At the second case, we have some limitations, first of all with number of ground-based stations. As the ionosondes provide no direct information on the profile above the maximum electron density (F2 peak), the topside part of this EDP is constructed by fitting a model to the peak value, so the complete EDP in ionosonde measurements consists of a measured bottomside and a modeled topside part. The use of ionosonde data for estimation of PEC contribution to GPS TEC over specific regions can be found in several papers (e.g. Belehaki et al., 2004; Mosert et al., 2007).

In the given research we estimate IEC on the basis of EDPs retrieved from the FORMOSAT-3/COSMIC radio occultation (RO) measurements. GPS RO data establish the basis for a new remote sensing technique for vertical profile information on the electron density of the entire ionosphere from satellite orbit heights down to the bottomside (Kirchengast et al., 2004; Jakowski et al., 2005; Liou et al., 2010). The new LEO mission – FORMOSAT-3/COSMIC (Taiwan's Formosa Satellite Mission #3/Constellation Observing System for Meteorology, Ionosphere and Climate) is a joint scientific mission of Taiwan and the US and was launched on April 15, 2006. The mission placed six micro-satellites into six different orbits at 700–800 km above the Earth's surface. The orbit inclination is 72°. Each microsatellite has a GPS Occultation Experiment (GOX) payload to operate the ionospheric RO measurements. Depending on the state of the constellation, COSMIC has been producing 1500–2500 good soundings of the ionosphere and atmosphere per day, uniformly distributed around the globe. This number of RO is much higher than ones obtained by similar missions before. The total number of ionospheric occultations for 2006–2011 is more than 3,000,000 (more than 50,000 profiles per month). Previous missions (e.g. CHAMP, GRACE) were able to produce only 4000–6000 RO profiles per month (only several hundred per day). Therefore, COSMIC data can make a positive impact on a global ionosphere study, providing essential information about the height electron density distribution; particularly over regions that are not accessible with ground-based measuring instruments such as ionosondes and GPS dual frequency receivers.

The objective of this paper was to illustrate the scope of RO measurements' application for the ionosphere/plasmasphere studies and to accentuate the importance of plasmaspheric contribution to the GPS TEC estimates, especially during periods of low solar activity.

2. Database

2.1. IGS data

The permanent GPS network provides regular monitoring of the ionosphere on a global scale with high resolution of TEC measurements. IGS Global Ionospheric Maps (GIMs) of TEC in the IONEX format were used. IONEX data are accessible at the ftp server: ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex. The GIMs are generated routinely by the IGS community with resolution of 5° longitude and 2.5° latitude and temporal interval of 2 h; one TEC unit (TECU) is equal 10^{16} electrons/m^2. Currently, there are three types of IGS GIMs: the final, rapid and predicted respectively. There are four IGS Associate Analysis Centres (IAACs) for the final and rapid ionospheric products: CODE, ESA/ESOC, JPL and gAGE/UPC. Detailed description of IGS GIMs computation and validation can be found in Hernandez-Pajares et al. (2009). The IAACs provide ionosphere maps computed with independent methodologies that use GNSS data from different set of GPS stations. These maps are uploaded to the IGS Ionosphere Product Coordinator, who computes the official IGS combined products. Since January 2008, this coordination is carried out by the GRL/UWM (Geodynamics Research Laboratory of the University of Warmia and Mazury in Olsztyn, Poland). During period of more than 10 years of continuous IGS ionosphere operation, the techniques used by the IAACs and the strategies of combination have improved in such a way that the combined IGS GIMs are now significantly more accurate and robust.

In this study, the final IGS combined GIMs produced by GRL/UWM were used to calculate the global maps of monthly medians of TEC values. These median TEC maps were generated for months of 2009 that corresponded to the equinoxes and solstices: March, June, September and December. So, for each month there were calculated 12 TEC median maps (2 h resolution).

2.2. COSMIC data

COSMIC RO measurements and products can be available from the Taiwan Analysis Center for COSMIC (TACC, http://tacc.cwb.gov.tw/en/) and the COSMIC Data Analysis and Archive Center (CDAAC, http://www.cosmic.ucar.edu/cdaac/). As it was already mentioned, COSMIC can provide 1500–2500 RO measurements per day, and more than 70% of the RO measurements can be successfully retrieved into EDPs, which are one of the most important products for space weather and ionospheric science. Fig. 1 illustrates the global distribution of the COSMIC RO points during one day (e.g. March 25, 2009). Derivation of the ionospheric electron density from radio occultation measurements is described in more detail by Tsai et al. (2001). At CDAAC, the ionospheric profiles are retrieved by use of